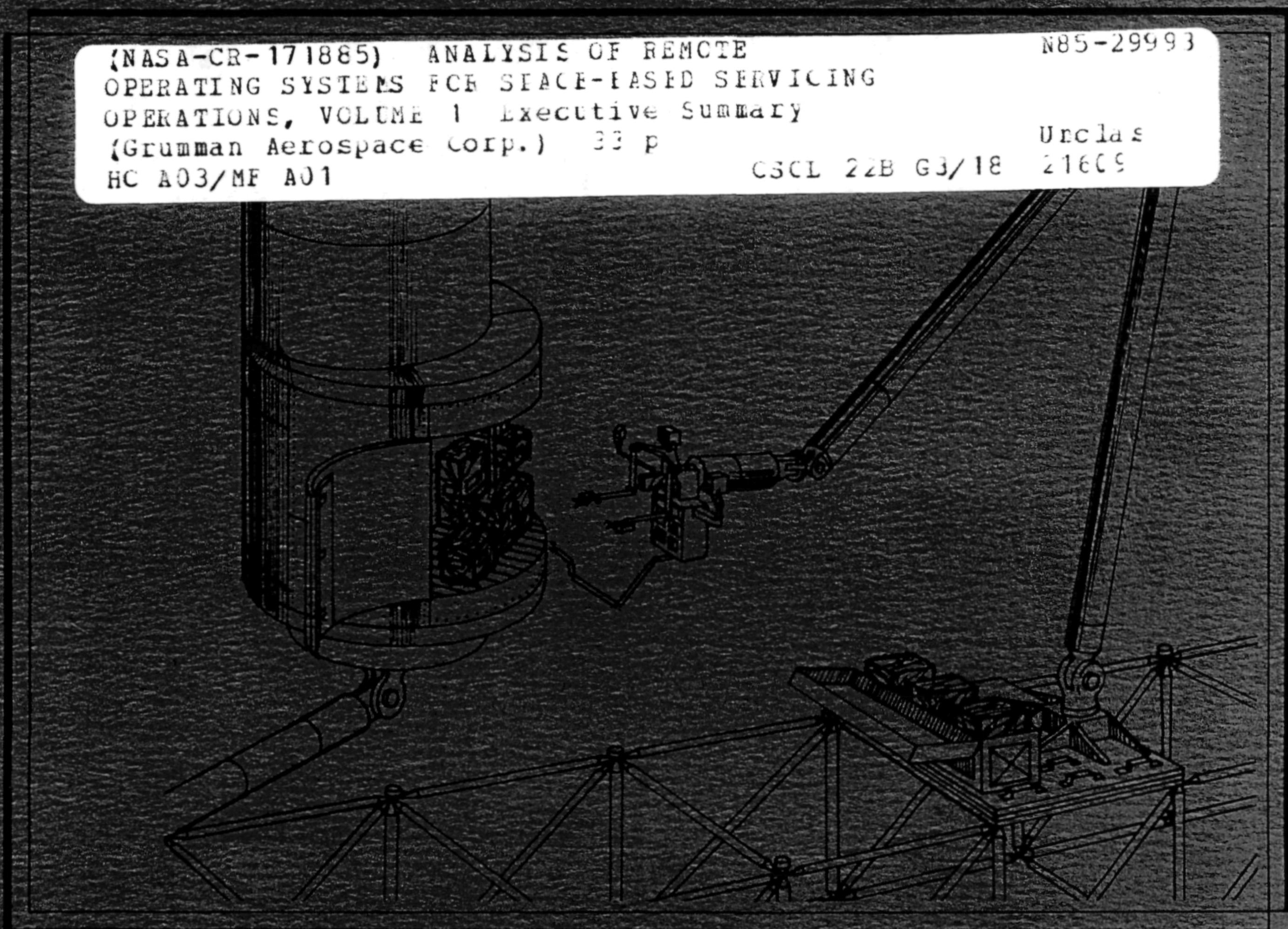
ANALYSIS OF REMOTE OPERATING SYSTEMS FOR SPACE-BASED SERVICING OPERATIONS, FINAL REPORT

Vol. 1 — Executive Summary



GRUMMAN CORPORATION

ANALYSIS OF REMOTE OPERATING SYSTEMS FOR SPACE-BASED SERVICING OPERATIONS, FINAL REPORT

Vol. 1 — Executive Summary

prepared for

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, TX 77058

by

Grumman Corporation
Bethpage, NY 11714

NAS9-17066
Report SA-ROS-RP-111-1

1 March 1985

PREFACE

This study was conducted for the Lyndon B. Johnson Space Center under NASA Contract NAS9-17066 by the Grumman Aerospace Corporation. Mr. Lyle M. Jenkins was NASA's Technical Monitor and Mr. Darrell R. Matula was the Contract Specialist for the study. Mr. Roy E. Olsen was the Grumman Study Manager.

The nine-month study was started on 27 February 1984. Phase 1 was completed on 27 May 1984 and Phase 2 was completed on 27 November 1984. A wide range of potential applications for space-based servicing, using remotely operated systems, have been identified and system concepts have been defined. A technology development program compatible with Space Station planning is also defined.

The major Grumman contributors to this study were:

- Erik Eriksen — Deputy Study Manager & Program Planning Task Leader
- Raymond Pratt — Mission Requirements Task Leader
- Stanis Coryell — Design Concepts Task Leader
- Chauncey Knapp — Design Concepts
- Christopher Horan — Design Concepts
- Vahe Jordan — System Costs

The Final Report for the study is presented in two volumes:

Volume 1 Executive Summary
Volume 2 Study Results

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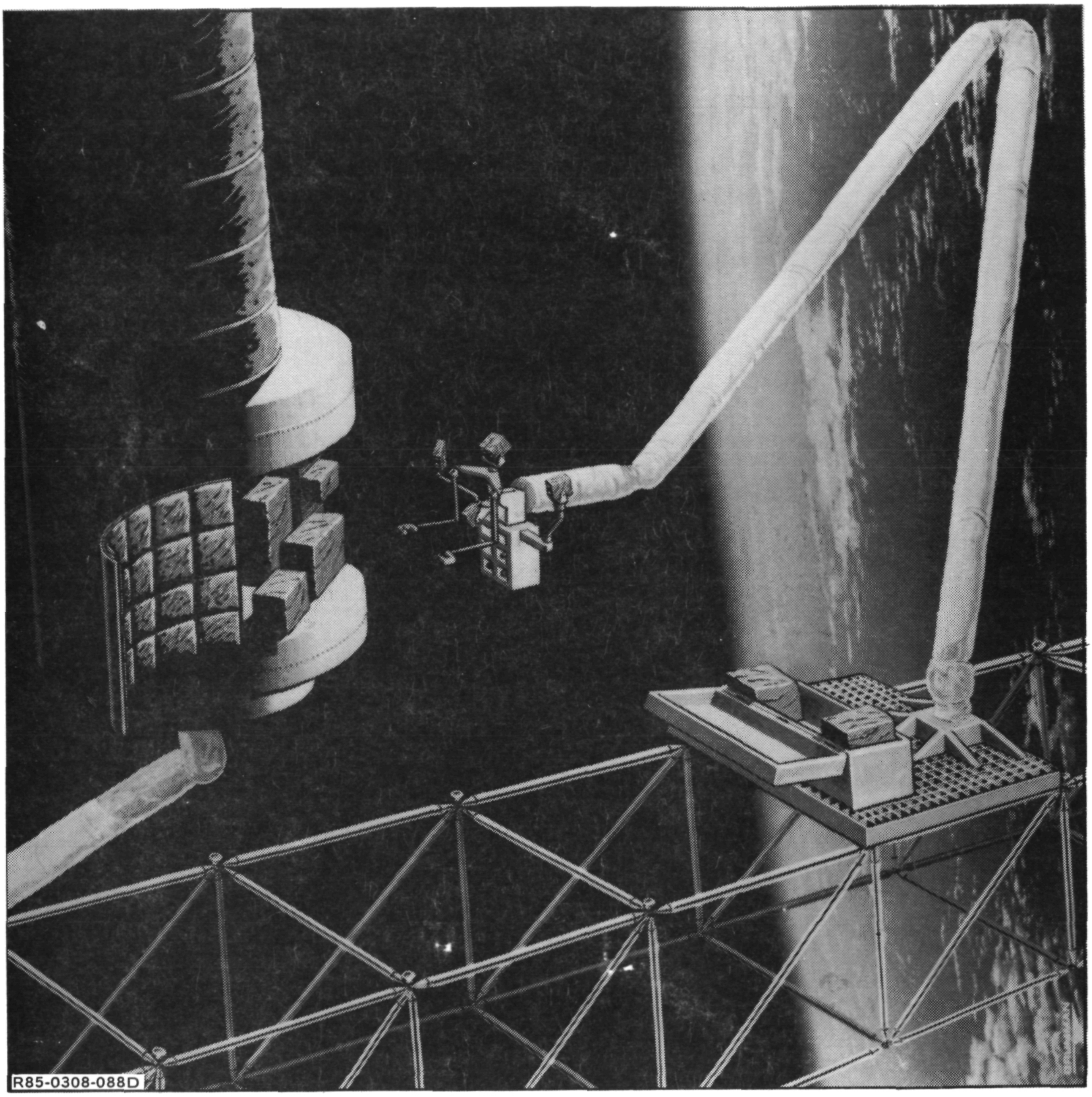
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CONTENTS

ILLUSTRATIONS

1 - INTRODUCTION

The space program to date has, by its very nature, depended on systems which were remotely operated because it primarily consisted of unmanned satellites and interplanetary vehicles. Automation and robotics technology, which is currently receiving much attention for terrestrial applications, offers the promise of significant benefits for in-orbit servicing. Recent developments in automation and robotics increase the importance of the applications for these systems in future space endeavors. With a Space Station, the servicing of attached payloads, co-orbiting satellites and remote satellites (Fig. 1-1) can provide significant reductions in program costs and increased effective use of resources in conducting space operations.

This report describes the results of a study which addressed the development of remote operating systems. Remote operating systems are defined as the equipment which provides the ability to perform useful work in space at distances ranging from close proximity to thousands of miles from a human operator. Included in the study are the identification of system requirements and the allocation of tasks to different types of remote systems. Three basic types of remote operating systems have been considered: teleoperation, telepresence and robotic. The goal of these systems is not to replace the human but to augment and extend the capabilities of the human in order to increase productivity and safety without sacrificing the unique human decision-making skills.

The Solar Max Mission vividly demonstrated the benefits to be gained from satellite servicing. Replaceable units, designed for rapid, simple servicing, included the Multimission Modular Spacecraft (MMS) modules. Servicing for the Main Electronics Box was a complex, lengthy task requiring extensive training.

Future in-orbit servicing will very likely involve systems that have been designed for servicing. Such systems may still involve complex servicing operations. It is also anticipated that there will always be equipment that cannot be designed for servicing. Therefore, although serviceable designs are the normal requirement, the

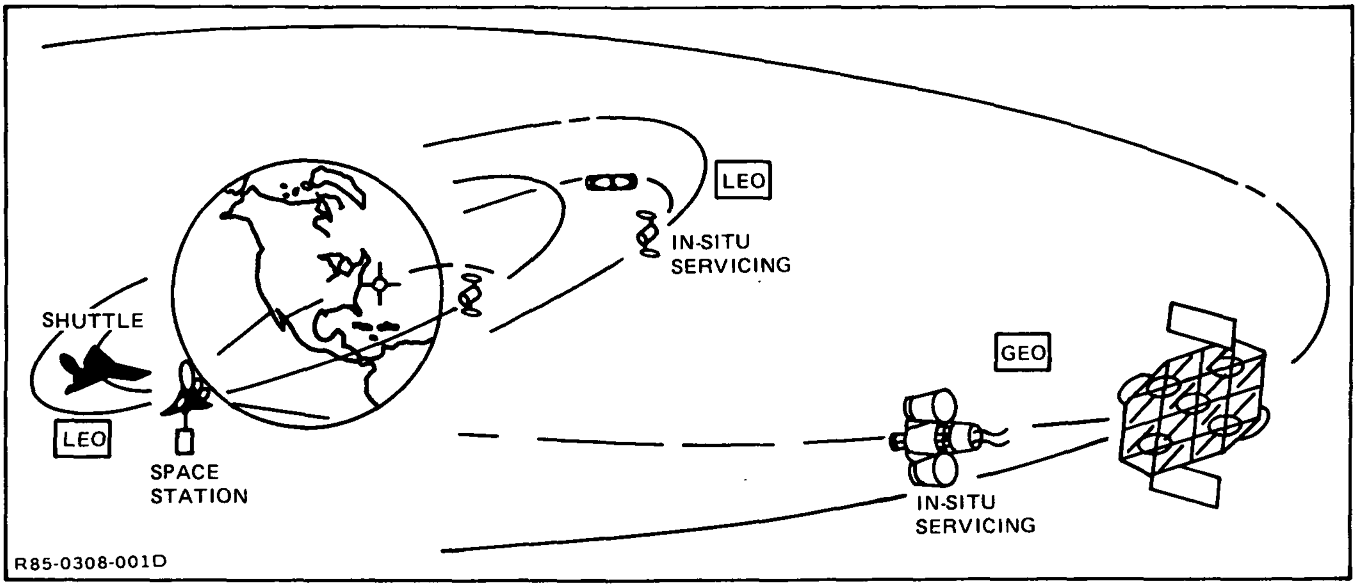

Fig. 1-1 Generic Service Sites

ability of concepts to perform more difficult tasks have been considered in the study.

1.1 SERVICING ON SPACE STATION

Systems for external servicing on the Space Station have been developed including attached payloads, such as earth resources sensors, temporarily attached satellites and stages, and subsystem elements of the Space Station itself. Such systems, in general, require the ability to move about the Space Station while remaining securely attached and must have accessibility to all regions to be serviced. The Space Station must supply the required utilities, such as electrical power, plus outfitting and storage provisions to the servicing systems. Crew accommodations must include the necessary equipment to support the operation of the remote systems.

1.2 SERVICING OF FREE FLYERS

Remote systems for servicing free flying spacecraft and platforms have also been developed. This involves a carrier vehicle which brings the remote servicing equipment to the free flyer and later returns it to a Space Station.

The infrastructure associated with this servicing concept (Fig. 1-2) consists of the spacecraft being serviced, the servicer vehicle system, and control stations on the Space Station and on the ground. In general, the physical separation between

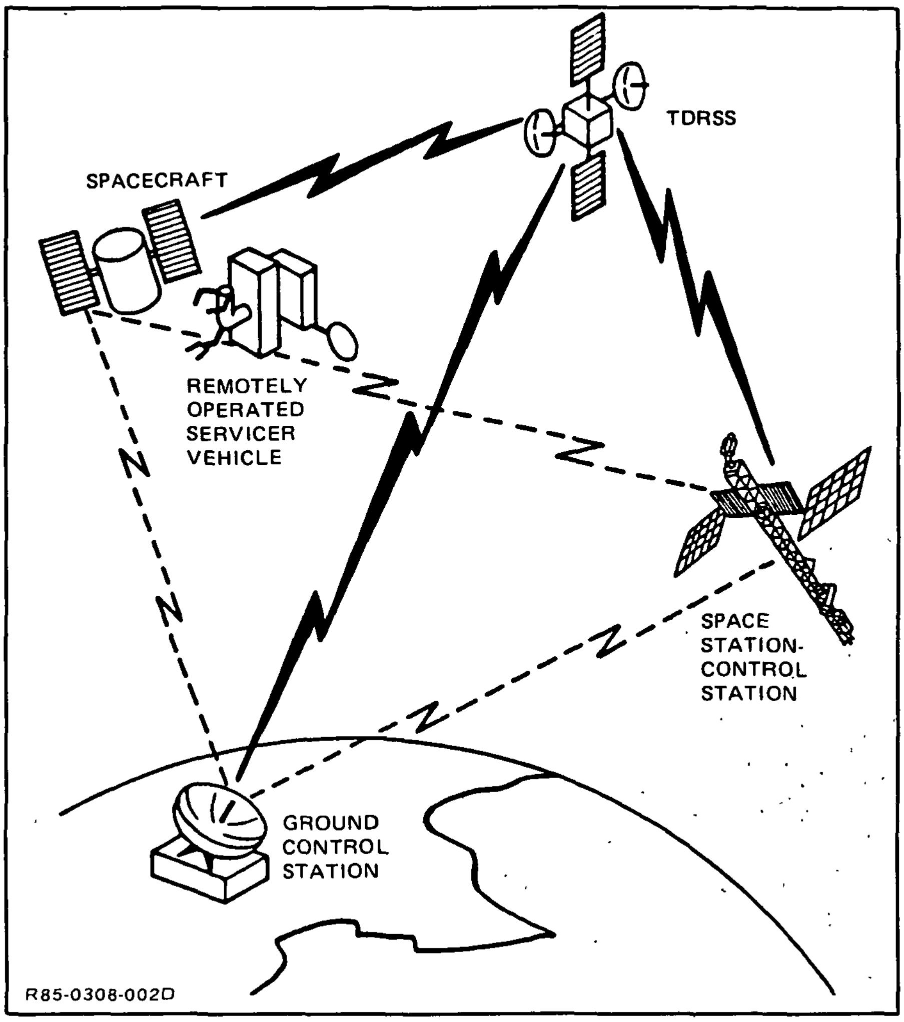

Fig. 1-2 Remote Operating Systems Infrastructure

these elements will require a data/command relay link for normal operations. The potentially long time delay resulting from this link is a significant consideration in the development of remote servicing systems.

2 - STUDY APPROACH

The study was conducted in two distinct phases (Fig. 2-1). In Phase 1, Requirements Development, which consisted of one three-month task, a group of ten missions were selected which provided a wide range of space-based servicing functions. These included the servicing of user equipment on the space station and *in situ* (or on-site) and the servicing of the space station itself. System requirements were developed for scenarios defined for the selected missions.

In Phase 2, Concepts Development, which consisted of three tasks, overall system concepts were developed (Fig. 2-2) for the selected missions. These concepts, which generally include worksite servicing equipment, a carrier system, and payload handling equipment, were evaluated relative to the configurations of the overall worksite. This included an evaluation of the candidate space station configurations and the logistics requirements for servicing. Figure 2-3 illustrates the matrix of space station and remote system approaches relative to the ten selected servicing requirements. Generic worksites for stage (OMV) servicing, satellite servicing, and assembly operations were identified which apply to any space station configuration. The power tower configuration, specifically the NASA reference configuration, was selected for the analysis of servicing of the space station. The resulting system concepts include a definition of the space station interfaces. Figure 2-3 also shows the two-dimensional matrix of approaches for free flyer servicing that were considered in this study.

Emphasis in the study has been on the worksite servicing equipment with other system elements considered only to the extent necessary to define such equipment concepts.

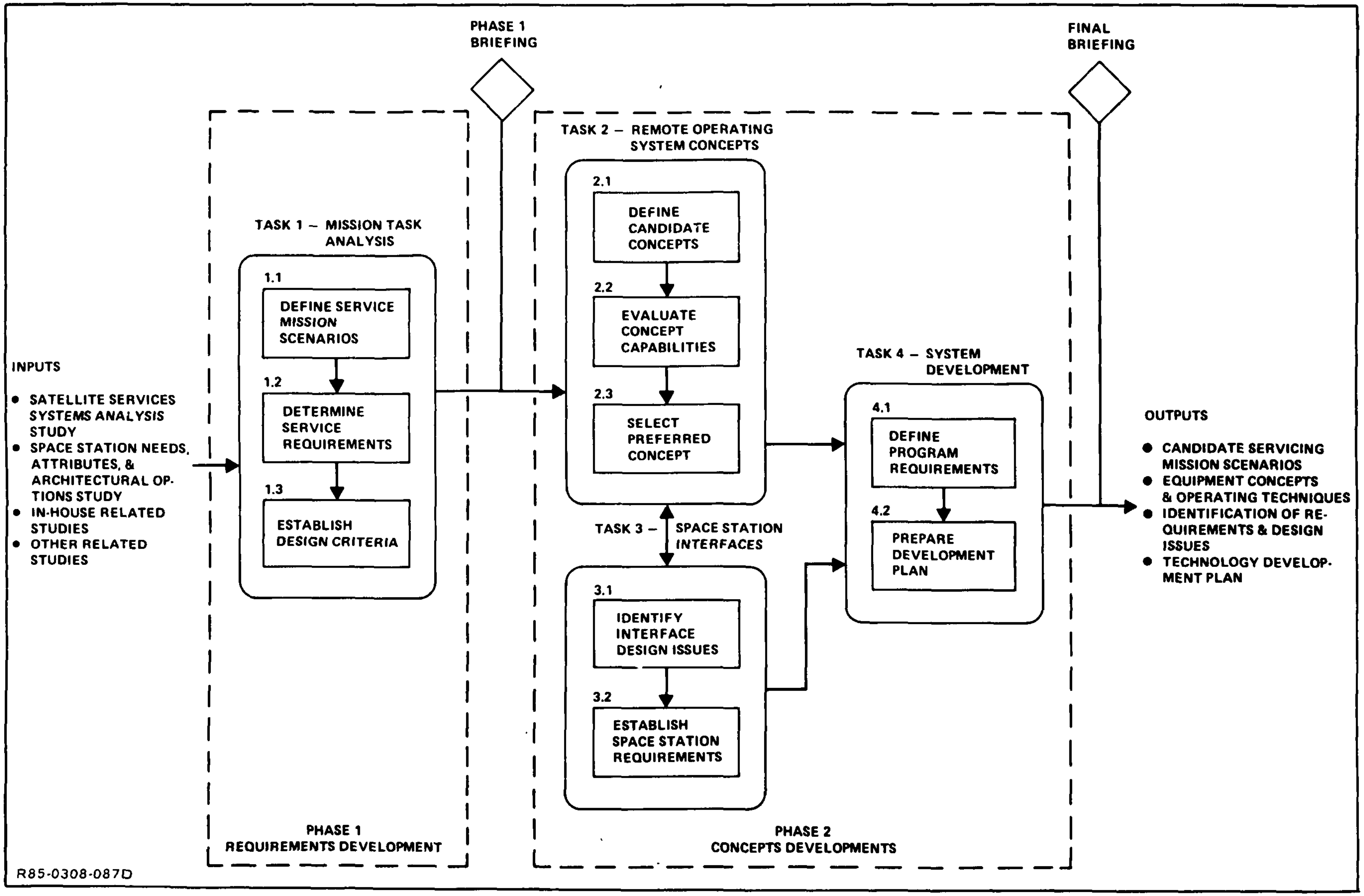

Fig. 2-1 Study Logic & Major Outputs

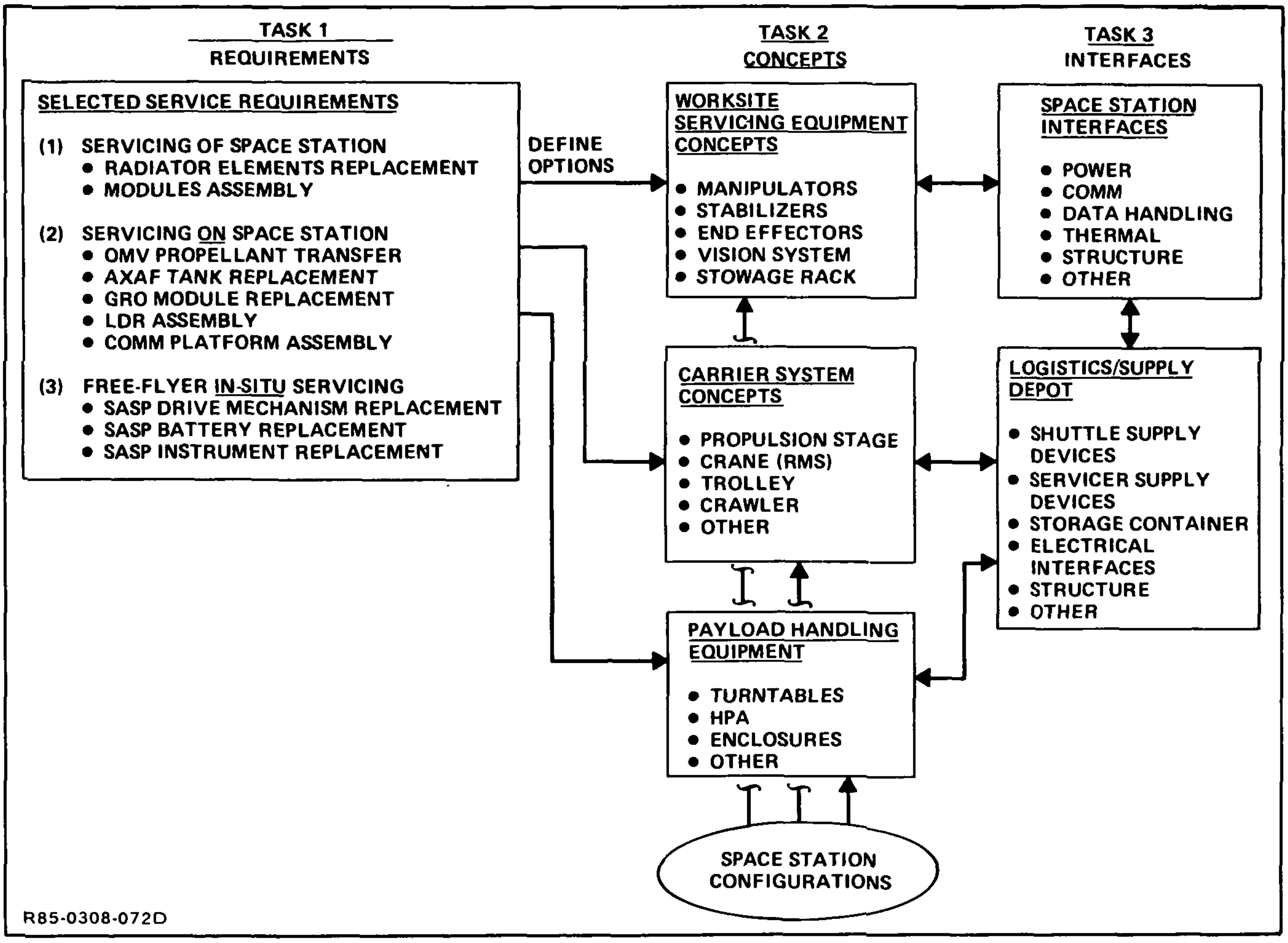

Fig. 2-2 Concepts Development – General

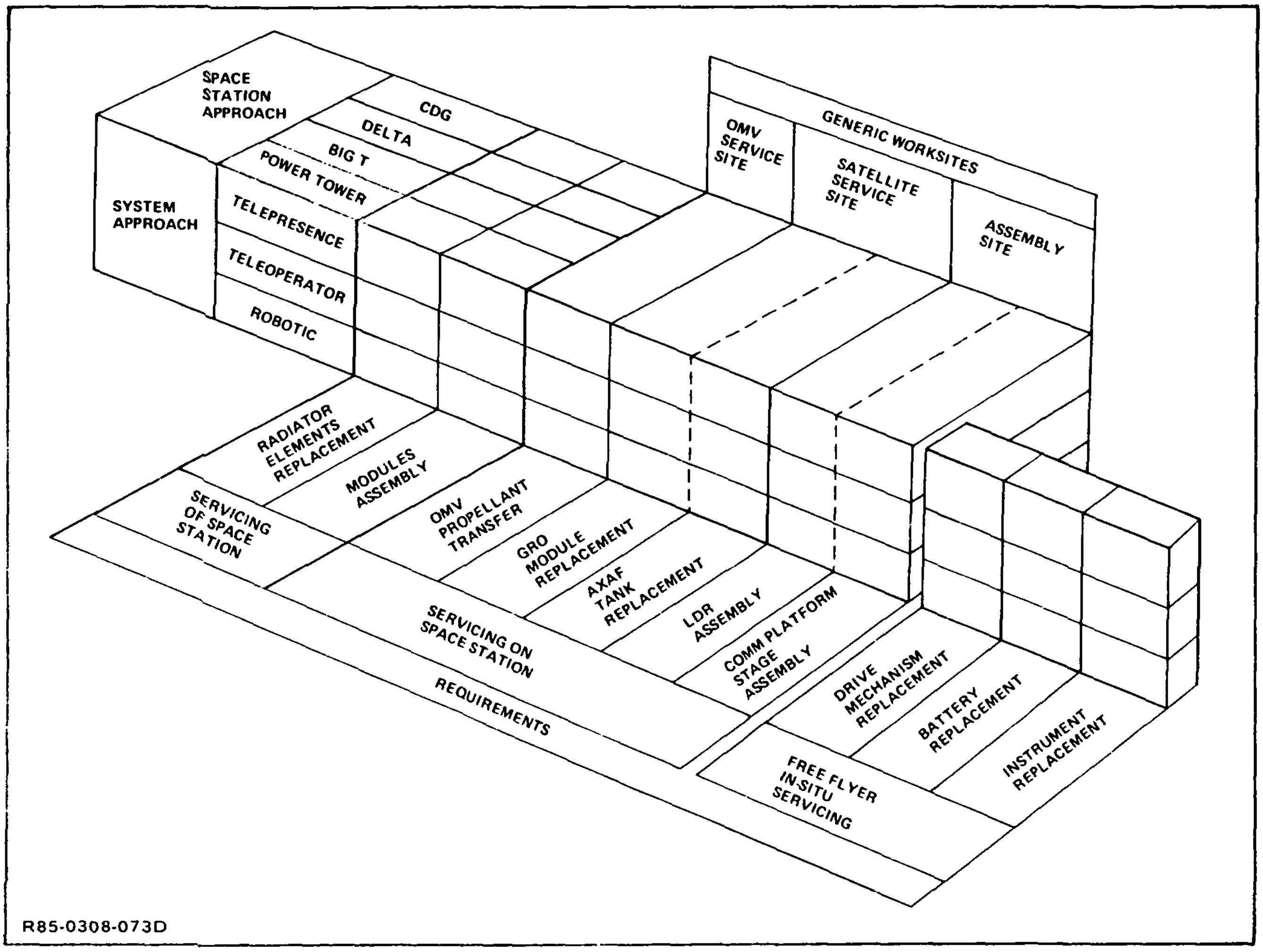

Fig. 2-3 Concepts Matrix

3 - STUDY RESULTS

This section summarizes the results of each phase of the study. In Phase 1, the general design criteria for remote operating systems were established by analyzing selected candidate missions. In Phase 2, candidate system concepts were developed for these missions by further analysis of the operational requirements and the estimated capabilities of particular system approaches.

3.1 REQUIREMENTS DEVELOPMENT

The initial phase of the study included the review of candidate servicing missions for the specified generic service sites. A preliminary group of fourteen candidate missions was selected based on considerations of mission time frame and the nature of potential servicing tasks. These missions were analyzed to determine candidate servicing operations.

The general functions required for satellite servicing (Fig. 3-1) extend from relatively simple resupply to upgrading of a satellite by incorporating new equipment. These functions may be required as a result of anticipated events, such as mechanical wear, or from unforeseen, uncontrollable occurrences such as a design flaw. The specific tasks indicated in the figure were selected for emphasis in the analysis of the reference missions.

SERVICING FUNCTION	REASONS FOR SERVICING	BASIC SERVICE REQUIREMENT
RESUPPLY	UNPLANNED LOSS OF EXPENDABLE • FAILURE • OTHER	REFILL TANKS OR ADD TANKS
	PLANNED USE OF EXPENDABLE • LOWER INITIAL LAUNCH WEIGHT	
REPLACE/REPAIR	UNPLANNED FAILURE • DESIGN FLAW • RANDOM FAILURE • WEAROUT • DELIVERY SYSTEM FAILURE/ANOMALY	• REMOVE AND/OR REPLACE FAILED EQUIPMENT • CORRECT CAUSE OF FAILURE
RECONFIGURE	PLANNED OR UNPLANNED NEW OR ADDED MISSIONS	ADD NEW EQUIPMENT AND/ OR MODIFY ARRANGEMENT OF OLD EQUIPMENT
UPGRADE	PLANNED OR UNPLANNED NEW TECHNOLOGY	ADD AND/OR MODIFY EQUIPMENT

SELECTED

- FLUID TRANSFER
- TANK REPLACEMENT
- ELECTRONICS REPLACEMENT
- "REPAIR"
- CONSTRUCTION

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Fig. 3-1 Requirements Development Service Tasks

Fluid transfer and tank replacement are the two basic techniques for replenishing expendables which is a common servicing requirement. Connecting and disconnecting fluid couplings are required in both cases. Electronics replacement describes the general removal and installation of electronics and electromechanical assemblies.

Repair and construction (or assembly) generally cover all other types of servicing activity including the reconfiguring and upgrading functions.

The final ten candidate missions selected from an initial group of fourteen are shown by the shaded items in Fig. 3-2 which also indicates the specific servicing

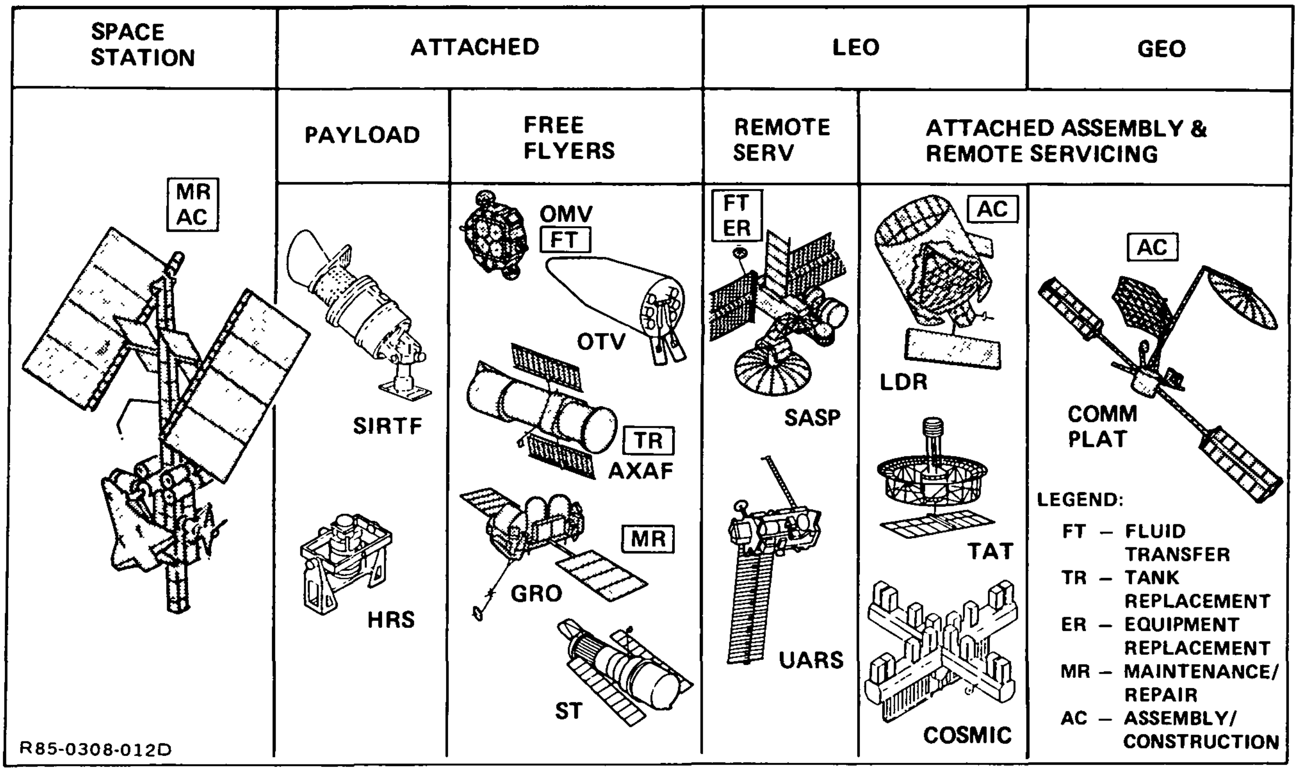

Fig. 3-2 Selected Servicing Missions

areas selected. Space station attached payloads were not selected because the functional servicing requirements are equivalent to those for attached free flyers.

A functional analysis was conducted for each of the candidate missions to determine particular service tasks of a generic nature. Three levels of functions were identified: first, the type of service to be provided, e.g., replace instruments; second, the specific item requiring service, e.g., subsystem component; third, the specific functions to implement the service. Comparison of servicing functions at the second level permit common representative functions to be selected.

The resulting servicing functions selected for the development of design criteria for remote operating systems are as follows:

- Servicing on the space station
  - Radiator panel replacement
  - Logistics module installation
  - OMV propellant transfer
  - AXAF tank replacement
  - LDR assembly
  - Communications platform/stage assembly
  - GRO subsystem module replacement
- *In situ* servicing
  - SASP drive mechanism replacement
  - SASP battery replacement
  - SASP instrument/manufactured products replacement.

The Science and Applications Space Platform (SASP) was chosen as the representative free flyer for servicing. Although this is a low earth orbit (LEO) spacecraft, the servicing tasks are equivalent to geosynchronous earth orbit (GEO) applications with the exception of the carrier vehicle.

General design criteria for the remote operating systems resulting from the analysis of the selected servicing tasks are shown in Fig. 3-3. The maximum and minimum values for the parameters shown were selected based on analysis of the specific servicing tasks. The indicated wide variations in complexity level and servicing frequency have been considered in the development and evaluation of candidate remote system concepts.

3.2 CONCEPTS DEVELOPMENT

Remote operating system concepts were developed for the selected candidate missions. Such systems consist of a variety of elements described, in general, by Figure 3-4 which is applicable to both free flyer and space station servicing. The *work system* is the element which performs the direct-contact operations associated with a task. The work system is held by a positioning arm which is carried by a transport vehicle. The other elements shown in the figure provide the other links between the operator and the remote task. The work system was the major area of interest in this study; the other elements were considered because of their impact on the work system design.

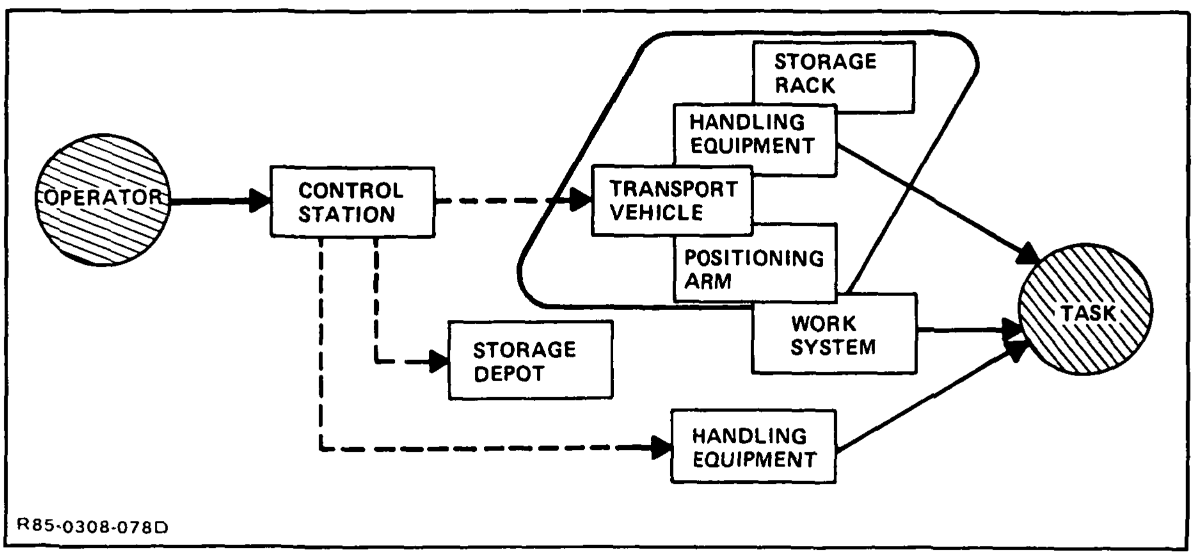

Fig. 3-4 Remote Operating System Elements

3.3 REMOTE WORK SYSTEM CONCEPTS

Remote work systems of three types have been considered: robotic, teleoperator and telepresence approaches. Baseline approaches for each type of work system (Fig. 3-5) were established to assess their applicability to the various servicing tasks. Robotic approaches are most applicable to servicing operations involving a well-defined, structured environment.

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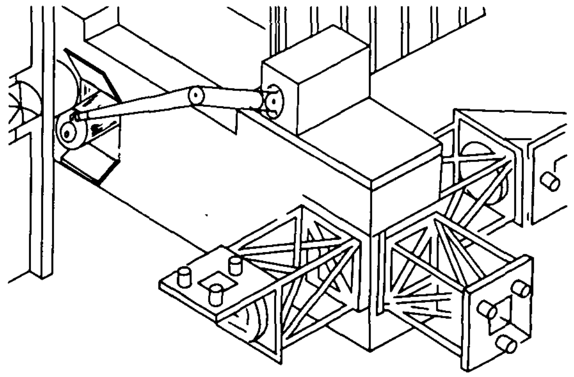
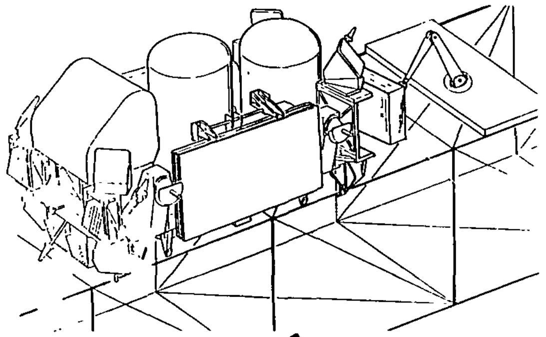
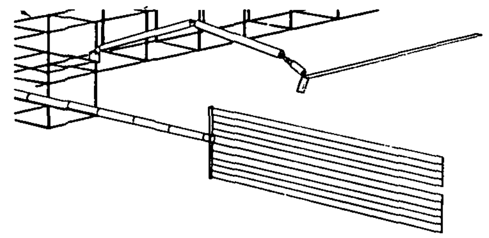
PLATFORM DRIVE
MECHANISM REPLACEMENT



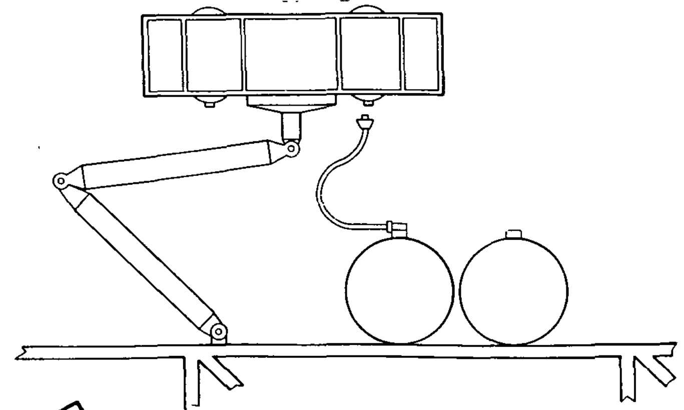
GRO SUBSYSTEM
MODULE REPLACEMENT



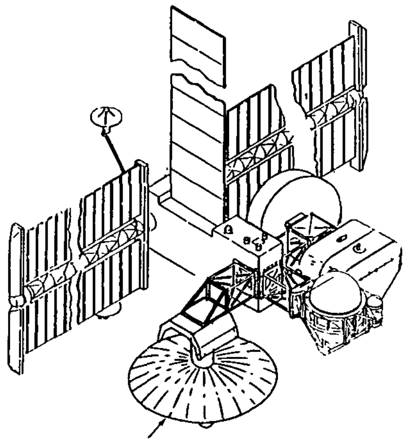
RADIATOR PANEL
REPLACEMENT



OMV PROPELLANT
TRANSFER



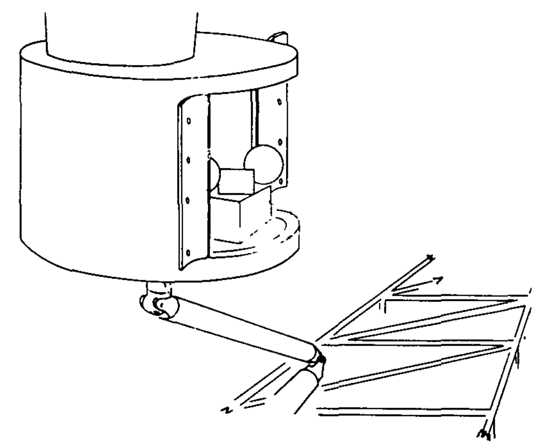
PLATFORM PAYLOADS
SERVICING



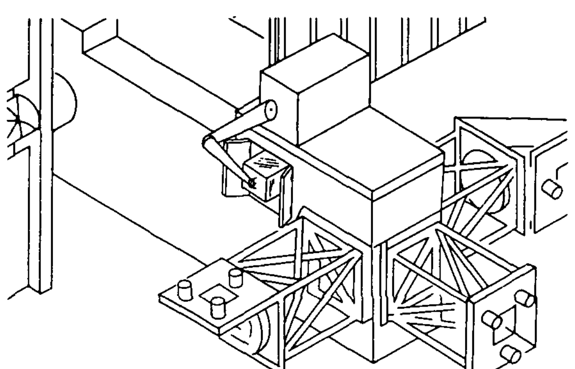
GENERAL DESIGN CRITERIA

ORU SIZE	MIN	MAX
• MASS	3 LBS	700 LBS
• DIMENSIONS	6 x 7 x 2 IN.	36 x 36 x 70 IN.
REACH	1.5 FT	20 FT
ACCESS HEIGHT	1 FT	6 FT
ACCESS WIDTH	1 FT	6 FT
ATTACH POINT SEPARATION	2 FT	20 FT
OBSTACLES	APPENDAGES/SOLAR ARRAYS	
LIGHTING AUGMENTATION	REQUIRED	
SPECIAL FEATURES	• DELICATE ITEMS • TIME DELAY	
COMPLEXITY LEVEL ASSESSMENT	LOW TO HIGH	
FREQUENCY	LOW TO HIGH	

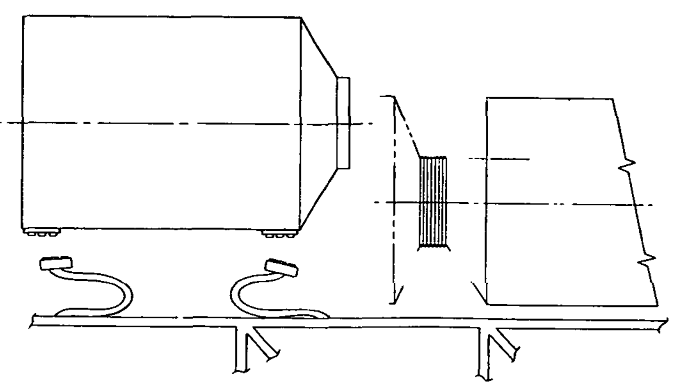
AXAF TANK
REPLACEMENT



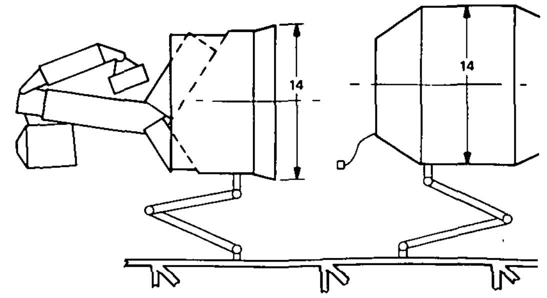
PLATFORM BATTERY
REPLACEMENT



LOGISTICS MODULE
INSTALLATION



COMM PLATFORM/STAGE
ASSEMBLY



LARGE SATELLITE
ASSEMBLY

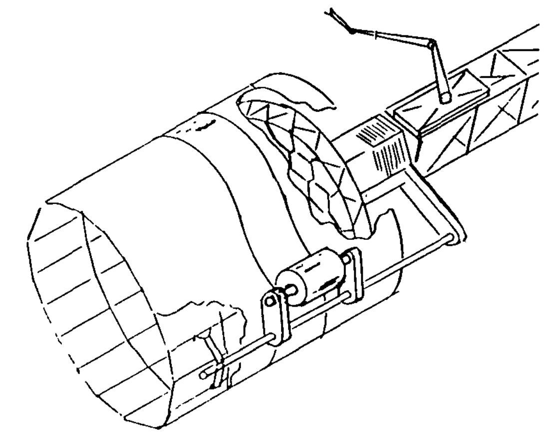


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Fig. 3-3 Requirements Development Summary

APPROACH	BASELINE SYSTEM
ROBOT	SINGLE 5 DOF ARM FORCE/TORQUE SENSOR VISION SYSTEM PROGRAMMED OPERATION
TELEOPERATOR	SINGLE 6 DOF ARM RESOLVED RATE CONTROL FORCE/TORQUE SENSOR MONO VIDEO SIMPLE GRAPHICS
TELEPRESENCE	TWO 7 DOF ARMS REPLICA CONTROL FORCE FEEDBACK STEREO VIDEO ADVANCED GRAPHICS
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Fig. 3-5 Remote Work System Approaches

If all required servicing were anticipated, spacecraft could be fully designed to permit robotic servicing. Telepresence approaches, while suitable for this situation, have the added versatility of being able to carry out real-time, unplanned operations.

Design concepts for each type of servicing approach were developed with the results illustrated in Fig. 3-6. The robotic work system consists of a single, five-degree-of-freedom manipulator mounted on the centerline of the base structure, housing the control and checkout electronics, and alternate end effectors. The attachment system is mounted to the bottom of the structure with a vision system located on the top.

The teleoperator work system consists of a single, six-degree-of-freedom dexterous manipulator in an anthropomorphic configuration mounted to a shoulder assembly. The system includes a combined end effector storage/electronics unit which is also the mounting structure for the attachment system and one of the vision system assemblies. Alternate end effectors for the manipulator and the attachment system are carried as required for the particular-servicing mission.

The telepresence work system consists of two dexterous manipulators in an anthropomorphic configuration combined with a stereo vision system. In addition, there are right and left camera mounted on positioning arms and a central *belly*

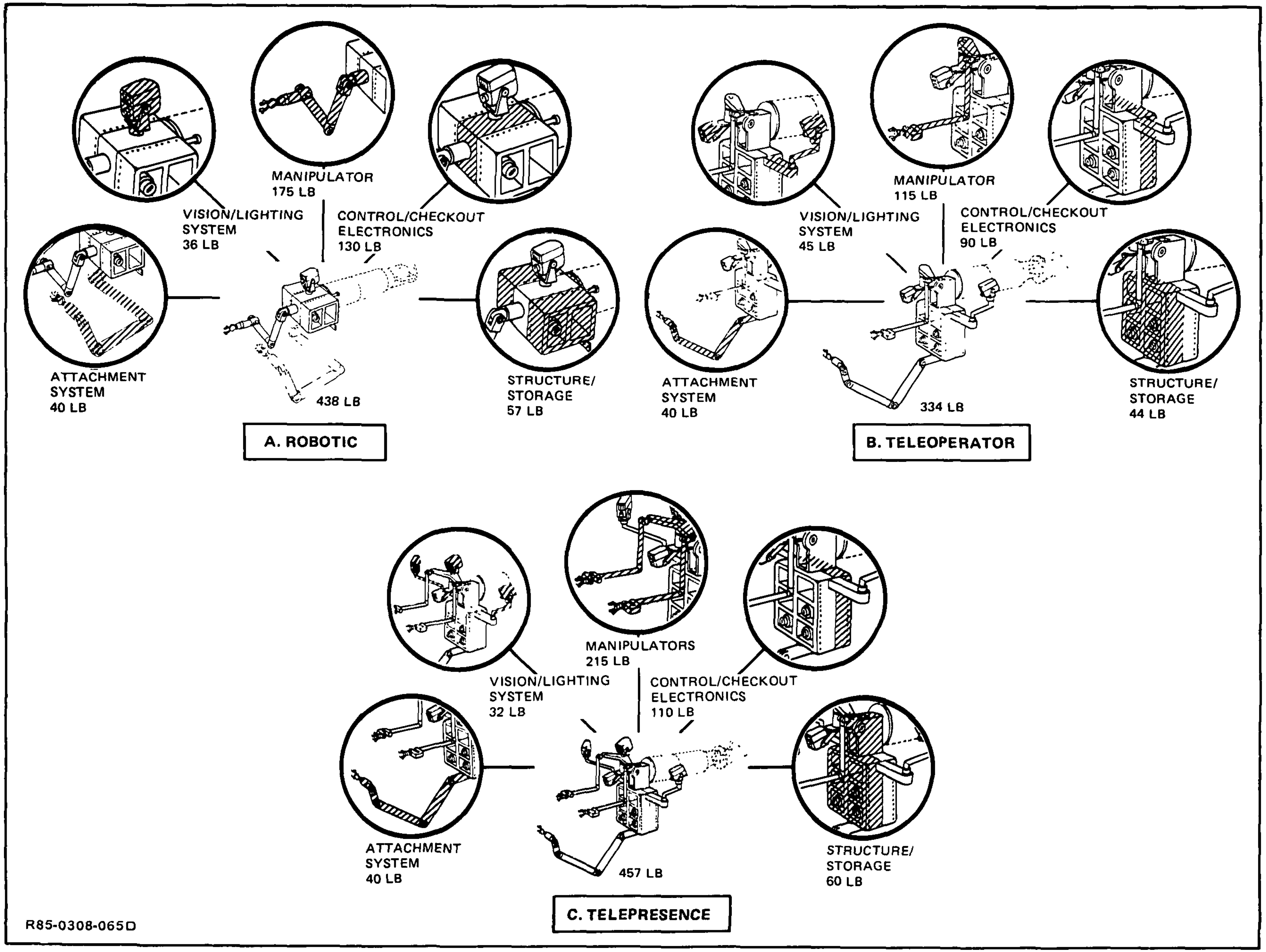


Fig. 3-6 Remote Work System Concepts

camera. Six end effector storage compartments are provided for use by both the manipulators and the attachment system. This assembly also forms the main support structure and electronics housing.

The subsystem requirements for the telepresence work system are presented in Fig. 3-7.

The applicability of each servicing approach relative to the candidate servicing missions was established (Fig. 3-8) based on the requirements of each service task and the assessment of the characteristics/limitations of each approach. The simplest acceptable approach was desired where robotic is considered the simplest and telepresence the most complex.

3.4 SERVICING ON SPACE STATION

The resulting system concept for servicing on the space station is illustrated in Fig. 3-9. The quantities shown in the table are the result of operations analysis for versatile combined servicing capability. The transport vehicle is shown supporting a stowage rack and a positioning arm which is holding a work system. An AXAF-type satellite is being held by a handling aid. Operation of the remote systems is under the control of the operator from a control station located elsewhere on the space station.

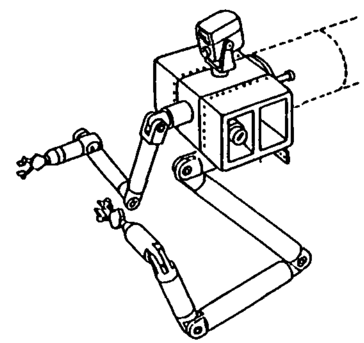
The general requirements for each of the major remote operating system elements, which interface with the space station, are presented in Fig. 3-10.

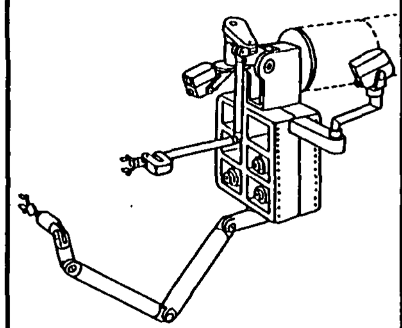
3.5 SERVICING OF FREE FLYERS

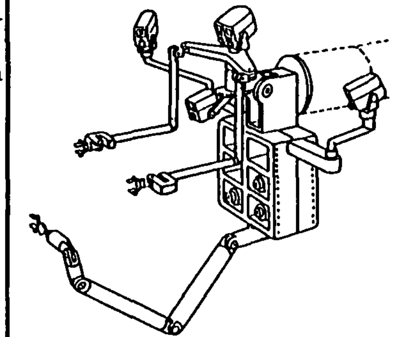
The resulting system concept for free flyer servicing is illustrated in Fig. 3-11, which shows a remote work system, a positioning arm, and a stowage rack on an OMV-type transport vehicle. The positioning arm is mounted on a *front-end* structure of the transport vehicle which also shows two replacement units attached to a storage rack. The basic system elements are comparable to the space station case although time delay considerations are more important in the case of the free flyer. A second positioning arm (not illustrated) was identified as valuable for servicing large free flyers, like the SASP, to provide accessibility from one berthing point. For such large platforms, this arm could be permanently attached to the free flyer. The total number of remote systems for free flyer servicing was not within the scope of this study because of its dependence on a specific mission model.

SUBSYSTEM	REQUIREMENTS (PER SYSTEM)	REQUIREMENT VALUE
ATTACHMENT SUBSYSTEM (MECHANICAL DEVICES FOR POSITIONING & STABILIZING THE REMOTE WORK SYSTEM WITH RESPECT TO THE WORK SITE	• QUANTITY • SIZE • NUMBER OF SEGMENTS • DOF • MAX TIP SPEED • MAX TIP FORCE • MAX TIP TORQUE • OPERATING VOLUME • END EFFECTOR TYPE(S) • END EFFECTORS, QUANTITY • END EFFECTOR DOF	1 8 FT 5 6 6 IN/SEC 100 LBF 40 IN-LB 2000 FT^3 TONG & MINI-GRAPPLER 2 1
MANIPULATOR SUBSYSTEM ELEMENT (ELECTRO-MECHANICAL DEVICES FOR HOLDING & MOVING TOOLS, EQUIPMENT & MATERIALS)	• QUANTITY • SIZE • DOF • MAX TIP SPEED • MAX FORCE • MAX TORQUE • OPERATING VOLUME • END EFFECTOR TYPES (INCLUDING TOOLS) • END EFFECTORS, QUANTITY • END EFFECTORS, DOF	2 4 FT 7 24 IN/SEC 20 LBF 10 IN-LB 275 FT^3 VARIOUS MISSION DEPENDENT 3 1
VISION SUBSYSTEM ELEMENT (ELECTRO-OPTICAL DEVICES TO PROVIDE VISUAL INFORMATION ABOUT THE WORKSITE)	• QUANTITY • INSTANTANEOUS COVERAGE ANGLE • TOTAL COVERAGE • SENSOR TYPE • DIMENSION • RESOLUTION • SENSITIVITY • PAN RATE • TILT RATE • ZOOM TIME • ZOOM RANGE (MAX)	5 (2 IN STEREO CONFIGURATION) 45 DEG SPHERICAL CCD 30 IN^3 180 K PICELS 5. FT-LAMBERTS 0 TO 10 DEG/SEC (VARIABLE) 0 TO 5 DEG/SEC (VARIABLE) 10 SEC SEL. 10:1
LIGHTING SUBSYSTEM (EQUIPMENT TO ILLUMINATE THE WORKSITE)	• COVERAGE ANGLE • INTENSITY RANGE • CONTROL MODE	90 DEG VARIABLE AUTOMATIC
CHECKOUT SUBSYSTEM (EQUIPMENT TO TEST THE OPERATION OF SERVICED UNITS)	• FUNCTIONS • MECHANICAL INTERFACES • ELECTRICAL INTERFACES	VARIABLE PROGRAM STND & SPECIAL PURPOSE STND & SPECIAL PURPOSE
CONTROL ELECTRONICS SUBSYSTEM (ELECTRONIC UNIT TO MONITOR AND CONTROL THE OTHER ELEMENTS)	• MISSION FUNCTIONS • HOUSEKEEPING FUNCTIONS • ELECTRICAL INTERFACES	N/A N/A N/A
STRUCTURE/STORAGE SUBSYSTEM (PROVIDE STRUCTURAL SUPPORT FOR OTHER ELEMENTS, STORAGE FOR END EFFECTORS & MOUNTING INTERFACE) R85-0308-077D	• SIZE • ATTACHMENTS, QUANTITY • ATTACHMENTS, SIZE RANGE • MOUNTING INTERFACE	CONCEPT DEPENDENT CONCEPT DEPENDENT CONCEPT DEPENDENT STANDARD RMS GRAPPLE FITTING

Fig. 3-7 Remote Work Systems – Requirements Summary







		• SINGLE 5 DOF ARM • FORCE/TORQUE SENSOR • VISION SYSTEM • PROGRAMMED OPERATION	• SINGLE 6 DOF ARM • RESOLVED RATE CONTROL • FORCE/TORQUE SENSOR • MONO VIDEO • SIMPLE GRAPHICS	• TWO 7 DOF ARMS • REPLICA CONTROL • FORCE FEEDBACK • STEREO VIDEO • ADVANCED GRAPHICS
SERVICING ON SPACE STATION	• RADIATOR PANEL REPAIR	√	√	
	• LOGISTICS MODULE INSTALLATION		√	√
	• OMV PROPELLANT TRANSFER	√	√	√
	• AXAF TANK REPLACEMENT		√	√
	• LDR ASSEMBLY		√	√
	• COMM PLATFORMS/STAGE ASSEMBLY		√	
	• GRO SUBSYSTEM MODULE REPLACEMENT	√	√	
IN-SITU SERVICING (SASP)	• DRIVE MECHANISM REPLACEMENT		√	√
	• BATTERY REPLACEMENT	√		
R85-0308-066D	• INSTRUMENTS/MANUFACTURED PRODUCTS REPLACEMENT			√

Fig. 3-8 Work System Applicability

SYSTEM ELEMENT	QUANTITY
TRANSPORT VEHICLES	3
POSITIONING ARMS	2 LARGE 1 SMALL
STOWAGE RACKS	2
WORK SYSTEMS	2
CONTROL STATIONS	1 (2 OPERATORS)

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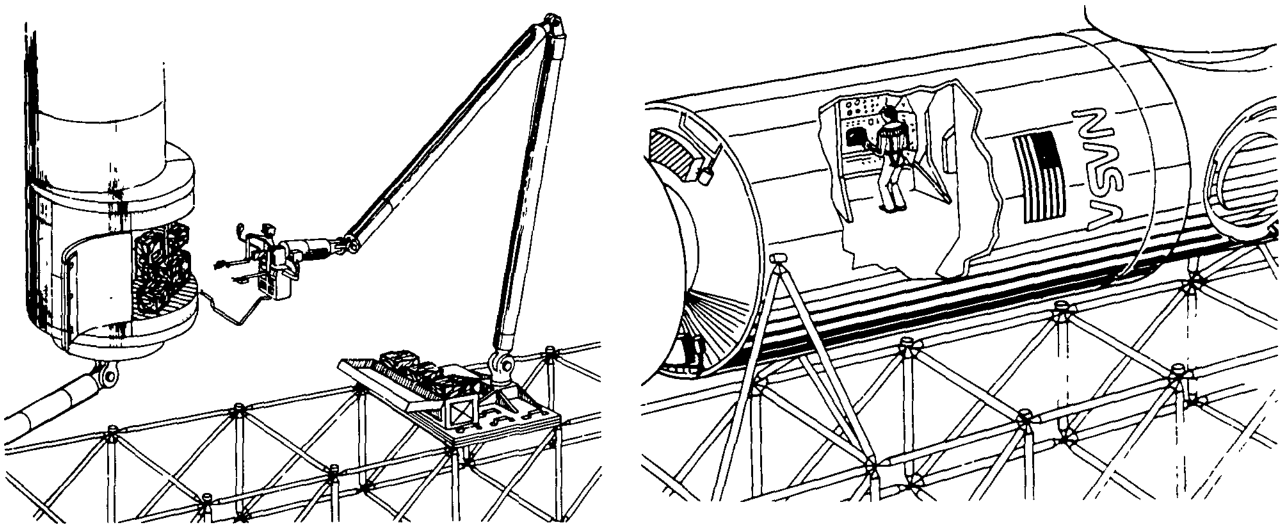

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Fig. 3-9 System Concept – Service on Space Station

ELEMENT	SPACE STATION REQUIREMENT
TRANSPORT VEHICLE	• PROVIDE GUIDES FOR VEHICLE SUPPORT & MOBILITY • PROVIDE MECHANICAL LOCOMOTION • PROVIDE POWER, COMM & DATA HANDLING
WORK SYSTEM	• PROVIDE STORAGE PROVISIONS • PROVIDE UTILITIES SUPPORT
HANDLING EQUIPMENT	• PROVIDE MECHANICAL MOUNTING • PROVIDE POWER, COMM, & DATA HANDLING
CONTROL STATION	• PROVIDE CONTROLS & DISPLAYS FOR OPERATING OTHER ELEMENTS • MONITOR PERFORMANCE OF OTHER ELEMENTS
STORAGE FACILITY (DEPOT)	• PROVIDE MECHANICAL MOUNTING • PROVIDE THERMAL CONTROL • PROVIDE INSTRUMENTATION

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Fig. 3-10 Station Elements – General Requirements

SYSTEM ELEMENT	QUANTITY
TRANSPORT VEHICLES	N/A *
POSITIONING ARMS	2 (SMALL)
STOWAGE RACKS	1
WORK SYSTEMS	1
CONTROL STATIONS	1 (1 OPERATOR)
*OMV PROGRAM DEPENDENT	

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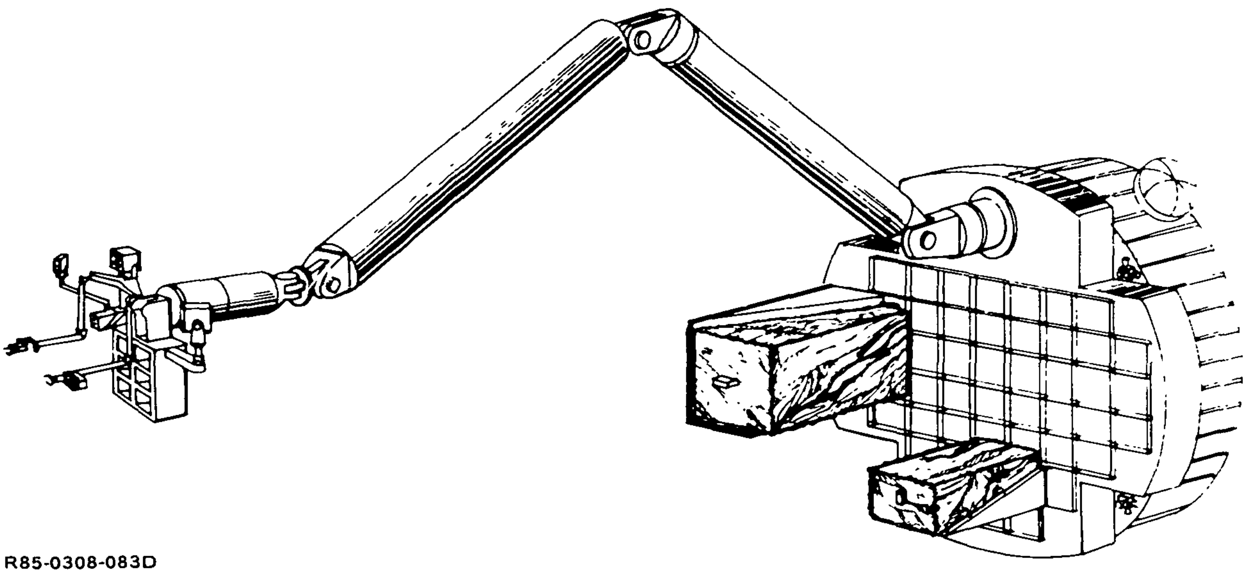

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Fig. 3-11 System Concept — Free Flyer Service

3.6 SYSTEM DEVELOPMENT

Programmatic concepts for technology development, testing, simulation, and flight demonstration in support of remote operating systems development were defined.

The five major elements needed to implement remote operations were evaluated (Fig. 3-12) in terms of schedule and technical risk relative to the space station program schedule and current technology level. The transport vehicle was judged to have a high schedule risk and the work system a high technical risk.

A development program for the remote work system was established (Fig. 3-13) which is keyed to the major milestones in the OMV and space station programs as specified during July 1984. The figure shows a development phase completed by the

ELEMENT	CURRENT TECHNOLOGY STATUS	SCHEDULE RISK	TECHNICAL RISK
TRANSPORT VEHICLE	EARLY CONCEPTS FORMULATED	HIGH	MODERATE*
POSITIONING ARM/ HANDLING DEVICE	• LARGE ARM (RMS) OPERATIONAL-MODS REQD • SMALL ARM DEVEL TEST ARTICLE-MODS REQD	LOW	LOW
WORK SYSTEM	• CONCEPTS FORMULATED • CRITICAL HARDWARE UNDER DEVELOPMENT	MODERATE	HIGH*
STORAGE RACK	EARLY CONCEPTS FORMULATED	MODERATE	LOW
CONTROL STATION	LIMITED TESTING OF CONCEPTUAL DESIGNS	LOW	MODERATE

*ELEMENTS CALLING FOR DEVELOPMENT EMPHASIS

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Fig. 3-12 Technology Risk Assessment

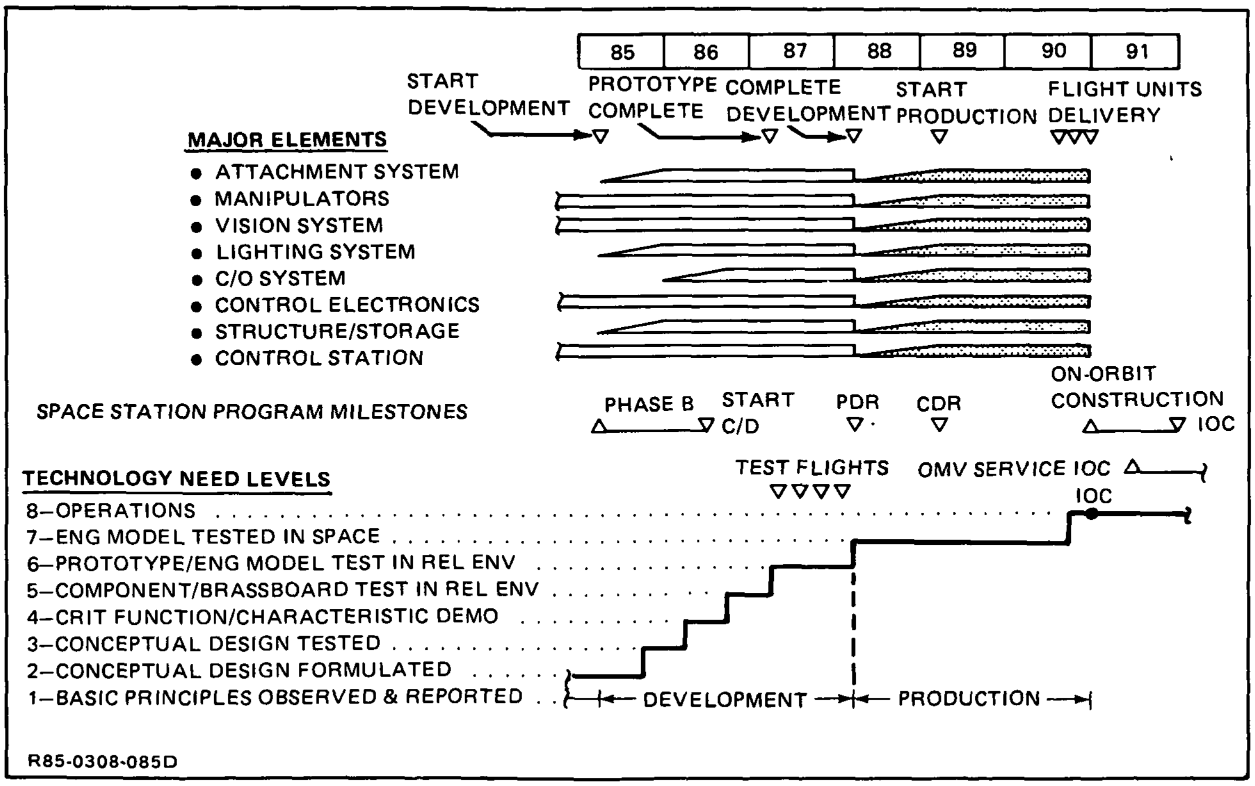

Fig. 3-13 Remote Work System Development

space station Preliminary Design Review (PDR) followed by a production phase providing flight units for use during initial operations. The progressive increases in the technology development levels resulting from the program are also indicated in the figure including a proof test in space of the major elements by PDR.

Flight demonstrations of the performance capabilities of critical components or systems are considered important steps in the development program. Shuttle flight test concepts to provide such verification include both an operational system performing a servicing task, and a general test bed concept for component evaluations, and are illustrated in Fig. 3-14. The Space Shuttle becomes a checkout and test facility for remote work systems with the astronauts in the role of test engineers.

Preliminary estimates of development and production costs for the remote work system concepts were derived (Fig. 3-15) using the Parametric Review of Information for Costing and Evaluation (PRICE) model. The program consists of one prototype and three production units. Cost estimates are driven by system size, weight, and complexity. These costs do not include the control station or flight operations.

Program costs are dominated by development costs for the low production, quantity assumed. Technology application to other space-based missions could change this result.

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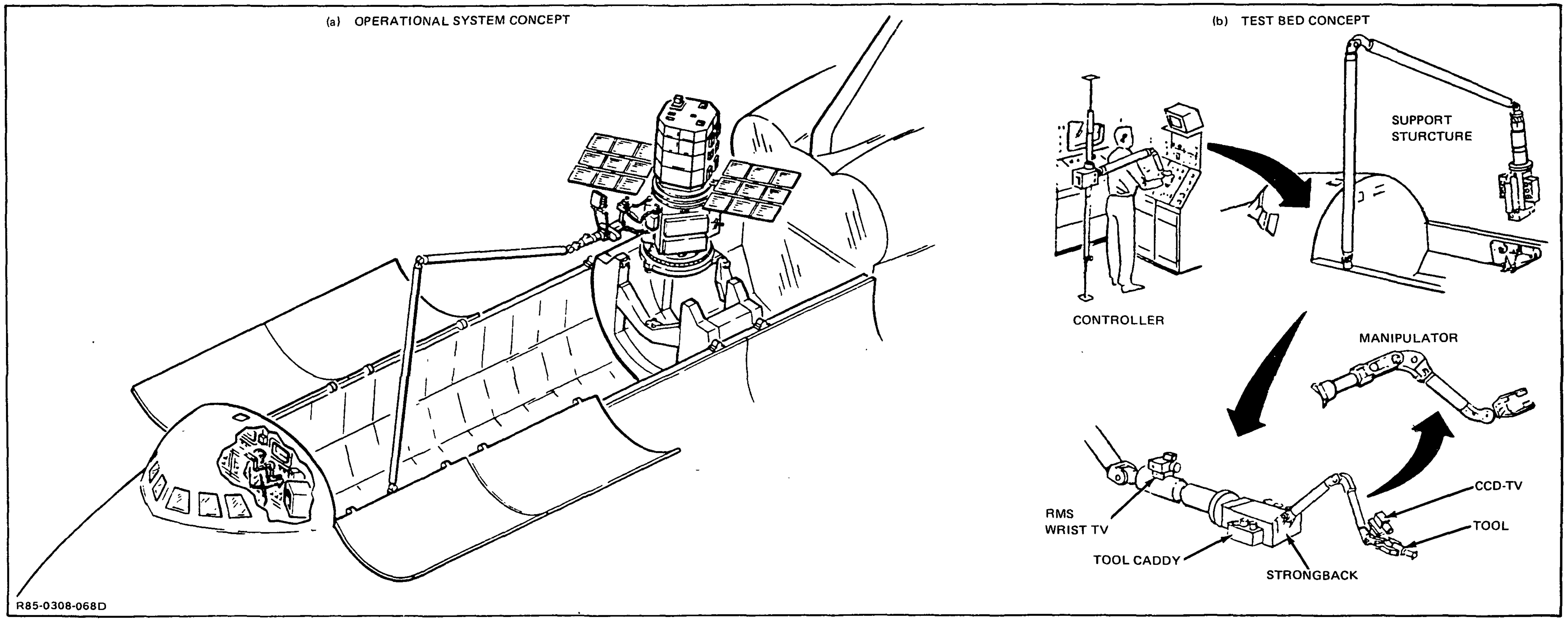

Fig. 3-14 Shuttle Flight Test Concepts

(CONSTANT 1984 $M)

	DEVELOPMENT		PRODUCTION		
	ENG	MFG	ENG	MFG	TOTAL
ROBOTIC	15.960	3.541	2.919	4.276	26.695
TELEOPERATOR	12.750	2.782	2.271	3.179	20.983
TELEPRESENCE	14.142	3.329	2.570	3.841	23.881

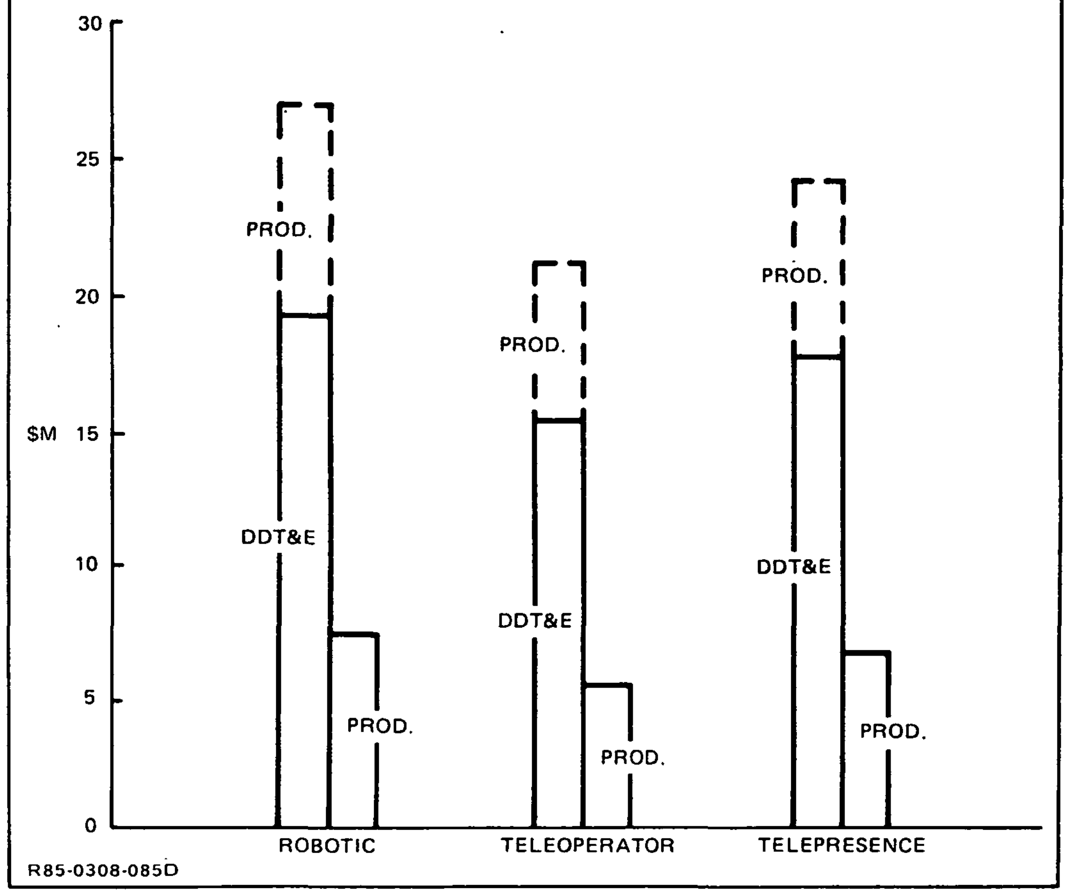

Fig. 3-15 Remote Work Systems – Relative Costs

4 - CONCLUSIONS

A wide range of potential applications for space-based servicing using remotely operated systems has been identified. Such systems are feasible but technology development is required, especially in the areas of the transport vehicle and the remote work system.

Spacecraft design characteristics significantly effect the selection of a particular approach for a remote work system. The wide variation in these characteristics has often resulted in a certain approach, e.g., robotic, being more appropriate than others for a particular mission. A lack of spacecraft design standardization generally results in more complex designs for remote work systems to provide near-universal servicing capability under nominal conditions. When potential contingency operations are also considered, design requirements for the remote work system become more stringent.

In general, robotic/teleoperator concepts are more appropriate for relatively simple, structured tasks. Telepresence/teleoperator concepts are more appropriate for mission applications which are described by relatively complex, unstructured tasks.

Only the telepresence system approach has the capability to provide all mission functions, although it may not be the optimum approach in some specific cases. The telepresence approach with supervisory control features can accommodate real-time variations in mission requirements while providing a degree of robotic capability.

An operational work system capability can be provided by 1991 for an estimated cost (for the flight system elements) of under $30 million.

5 - RECOMMENDATIONS

The development of remote operating systems technology should be accelerated to fully realize the potential benefits of space-based servicing in support of the space station program.

Key technologies for the remote work system and the carrier vehicle are especially critical. Development of the following elements of the remote work sytem is required:

- Manipulators
- Vision system
- Check out system
- Control electronics
- Control station.

Such development should emphasize the use of ground and flight test bed facilities for component and system testing and demonstration. Such an approach, which includes the use of NASA and contractor labs and simulators plus shuttle flights, is important to ensure early availability of operational systems.

Provisions for remote servicing in space station and platform designs should be encouraged as an important ingredient of the recommended development program. The incorporation of modular designs and standard interfaces will decrease the complexity of servicing systems.

The application of remote operating systems for other in-orbit activities, such as space station and platform construction, should be addressed to identify potential benefits to the space station program.

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